A Lightpath Length-Aware Adaptive Routing Algorithm for WDM Networks

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Abstract—This letter proposes an adaptive routing algorithm for wavelength-routed optical networks. It is essentially based on routing information originating from the optical layer and, contrary to current algorithms, it does not require the exchange of a large quantity of routing information. After identifying the critical effect of the lightpath’s length on the overall blocking performance, a simple penalty function is proposed to limit this length. Simulation results show that this algorithm outperforms most currently known algorithms recently proposed in the literature.

I. INTRODUCTION

In the past decade, many problems have been noted concerning in the management of the huge amount of bandwidth offered by wavelength division multiplexing (WDM) technology in long-haul networks. They are mainly related to photonic technology or optical control plane management. This letter addresses the control plane, more precisely the routing functionality. Certainly, the most well-known problem in this domain is the Routing and Wavelength Assignment (RWA) problem in wavelength-routed optical networks which consist of wavelength routing nodes interconnected with optical fibers. The RWA problem consists of determining a path between a pair of source and destination nodes, and assigning a free wavelength to all of the links on this all-optical path, commonly referred to as a lightpath, while respecting a desired objective and a set of assumptions and constraints.

For long-haul networks, the RWA problem is generally formulated in the context of optical network design and dimensioning according to two main assumptions. First, the routing of lightpath requests is static, meaning that the same fixed route is permanently chosen for a given source-destination pair. Route calculation is then conducted off-line since the computing time is irrelevant in this context. The most important criterion resides in serving a maximum number of users for a minimal cost. Second, routing and wavelength assignment are treated as separate subproblems, as it is very difficult to solve the RWA problem as a whole. Furthermore, the routing subproblem is generally solved at the packet level, as it is difficult to obtain information from the optical layer.

Static routing is essentially based on traffic projection, meaning that this routing efficiency is related to accurate projection. Unfortunately, making an accurate traffic projection is an arduous task due to the tremendous fluctuations in the quantity and nature of data traffic. In order to reduce detrimental business impact due to an inaccurate traffic projection, it is necessary to have tools that enable a quick reconfiguration of the optical network to maximize the resource utilization [1]. Therefore, fixed routing should be replaced by adaptive routing in order to provide sufficient flexibility to the network and accommodate dynamic traffic. In adaptive routing, the route from a source to a destination is chosen dynamically, depending on the network’s state.

Several adaptive routing algorithms which consider the number of available wavelengths have been proposed. Most of them are based on alternate routing, where a set of alternate routes is considered sequentially if the primary route is unavailable for the current lightpath connection request [2], [3]. The performance of these algorithms is highly sensitive to the number of considered alternate routes. Obviously, considering an exhaustive set of alternate routes would give the best performance, although it would incur a very high level of computational complexity. Least congested path (LCP) is an alternate path routing algorithm where the congestion of a link is determined by the number of available wavelengths and the path’s congestion is determined by the most congested link in this path. Simulations have shown that using shortest path first (SPF) routing before choosing the LCP generates better performance than using the LCP routing alone, in terms of blocking probability [4]. This shows the importance of the lightpath length on performance. In a recent study, Yoo et al. [5] proposed four adaptive routing algorithms which consider the available wavelengths. The first algorithm, called near-maximum available wavelengths (NAW), tends to maximize the number of common wavelengths from the source to the destination, and is based on source routing. The others are hop-by-hop based, and focus on minimizing the blocking probability by providing greater opportunities for the continuity constraint to be satisfied, thus increasing the complexity. Although the lightpath’s length has been identified as a critical parameter, it has yet to be considered in the route computing process.

This letter proposes an adaptive routing algorithm which considers information about the number of available wavelengths for each link with minimum computing overhead and a penalty on the lightpath’s length. Experience with unicast routing in IP networks has shown that in practice, only simple algorithms which introduce minimum communication overhead are useful, e.g., RIP.

The remainder of this letter is as follows. Section II describes the new adaptive routing algorithm proposed. In Section III, an example is used to illustrate the different steps of the algorithm. Section IV presents and analyzes simulation results for blocking probability and lightpath’s length. Finally, section V summarizes this letter.
II. THE PROPOSED ALGORITHM

This new proposal is based on the following two observations: first, it is important to decrease resource consumption by reducing lightpath lengths, which can be achieved through SPF routing; second, routing through least congested paths allows load sharing and thus preserves resources on critical links for future connections. Intuitively, these techniques reduce the blocking probability. However, they run in opposite directions. In fact, since SPF routing is not aware of the network status, it cannot perform load sharing. On the other hand, LCP routing may choose longer paths in order to avoid congested links, which is resource wasteful.

This new algorithm combines both LCP and SPF routing by introducing a penalty function \( f(n_h) \) which is decreasing in the number of hops \( n_h \). Let \( n^i_\lambda \) be the minimum number of available wavelengths for all links constituting the path from the source \( s \) to node \( i \), and \( n^i \) be the number of hops in this path. If a labeling algorithm is applied, the node label will be given by the following weighting function:

\[
    w(i) = n^i_\lambda f(n^i_h).
\]

This explains why this routing is called Penalized Lightpath Routing (PLR). The node with the maximum weight will be chosen for each iteration. In the event of a tie, the node with the lowest number of hops is chosen. The PLR algorithm assumes that the number of free wavelengths available for each link is exchanged via any extended link state routing protocol, like OSPF or IS-IS. Unlike NAW, which requires the identification of each free wavelength, the PLR algorithm, based also on a source routing approach, does not require any information about the wavelength bands, which considerably reduces the amount of information exchanged.

Define \( l^i_{s,j} \) as the number of available wavelengths on the link (or fiber) between nodes \( i \) and \( j \), and \( P \) as the set of permanent labels. The PLR algorithm is described as follows:

Input: A graph \( G(N, E) \) where \( N \) is the set of wavelength routing nodes, and \( E \) the set of fiber links; a connection request between nodes \( s \) and \( d \).

Step 1: \( w(j) = l^i_{s,j} f(1) \) for \( j \neq s \). \( w(s) = 0 \), \( P = \{s\} \).

Step 2: Find \( i \notin P \) such that \( w(i) = \max_{j \in P} w(j) \).

- If \( \exists k \) such that \( w(i) = w(k) \), then if \( n^k_h < n^i_h \), then \( i := k \).
- If \( P := P \cup \{i\} \).
- If \( P = N \) or \( i = d \), then stop.

Step 3: For all \( j \notin P \)

- If \( w(j) < \min(n^i_\lambda, l^i_{s,j}) f(n^i_h + 1) \), then \( w(j) := \min(n^i_\lambda, l^i_{s,j}) f(n^i_h + 1) \);
- \( n^i_j := \min(n^i_\lambda, l^i_{s,j}) \);
- \( n^i_h := n^i_h + 1 \).

Step 4: Go to Step 2.

In Step 1, all marked nodes are directly connected to the source. This is why all nodes will have the same penalty \( f(1) \), which typically equals 1. In Step 2, the algorithm finds a node with the maximum weight and breaks ties, when required. Step 3 updates temporary labels. Finally, note that a predecessor list, where each node’s entry contains the index of its predecessor in the shortest path towards the source, must be maintained in order to subsequently reconstruct the final path.

Both the PLR and NAW are based on Dijkstra’s procedures, so they are basically of \( O(N^2) \) time complexity. However, NAW incurs an additional overhead \( p \) for the logical AND, which depends on the number of wavelengths per link, so its overall complexity is \( O(pN^2) \) [5]. PLR does not require any additional overhead, so its overall complexity is maintained at \( O(N^2) \). Finally, notice that the PLR does not assign wavelengths, although if it does not return a solution, it indicates that the assignment problem has no feasible solution. For most RWA algorithms where routing is not aware of the optical information, the routing algorithm returns a feasible path in spite of the unavailability of the wavelengths. Since it considers wavelength continuity, the NAW facilitates wavelength assignment, although it incurs extra overhead.

III. ILLUSTRATIVE EXAMPLE

To illustrate how the PLR algorithm works, consider the undirected graph in Figure 1, where each link is bidirectional with one fiber in each direction. Each link is labeled with the number of available wavelengths. This example assumes that the same number of wavelengths is available in each direction, and attempts to route a connection request between nodes \( s \) and \( d \) using one wavelength. The following simple penalty function is selected:

\[
    f(n^i_h) = \frac{1}{n^i_h}.
\]

Figure 1 reports the information regarding the PLR algorithm progress. The superscript inside each node indicates the order in which this node becomes permanent, i.e., belongs to set \( P \), which also indicates the iteration number. The following order is thus obtained: \( s, b, a, e, c \) and \( d \). Labels stacked near the nodes have the following meaning: iteration number: (previous node, metric). The crossed labels indicate they do not contain better metrics than the existing ones, thus they will be ignored in subsequent iterations. For example, the direct path from \( s \) to \( a \) has 4 available wavelengths, yielding a metric of \( 4/1 = 4 \), and the path which transits via \( b \) has 5 available wavelengths, but it crosses 2 links, yielding a metric of \( 5/2 = 2.5 \), which is smaller than the direct path metric, even if this longer path carries more available wavelengths. The destination node can also exhibit this behavior. If the
SPF is applied, node $d$ can be reached in 2 hops, but in this case link $(b, d)$ will be blocked for future requests since the unique available wavelength will be assigned to the current request. On the other hand, if an LCP is applied, the optimal path would be $(s, b, e, c, d)$ which has 5 available wavelengths, but if there is continuity, one wavelength must be taken off from the 5 links on this path. Thus, the PLR circumvents the drawbacks of both the SPF and LCP since it constructs an optimal path with 4 available wavelengths and only 3 links.

IV. NUMERICAL RESULTS

The call blocking performance and the mean lightpath lengths of the PLR algorithm were compared to that of the NAW, LCP and SPF algorithms. The comparison was restricted solely to these algorithms for two reasons. First, it was shown in [5] that NAW outperforms all other algorithms, including the alternate routing based algorithm FPLC-k proposed in [2]. Second, both LCP and SPF provide the least congested and minimum hop paths, respectively. The NSF network of 19 nodes and 32 links was selected to evaluate these algorithms. Each bidirectional link consists of two fibers, one in each direction, with each fiber containing 40 wavelengths. All simulations assume the incremental traffic case where all channels are free at the initial time, then connection requests arrive sequentially according to a uniform distribution, a lightpath is established for each admitted connection, and it remains in the network indefinitely. A first-fit wavelength assignment scheme is used for all algorithms. Finally, the same penalty function as in (2) was selected.

Figure 2 shows the blocking probability of each RWA scheme as a function of the number of connection requests. In order to achieve accurate results with a small 95% confidence interval, 20 simulations were performed for each number of connection requests. Also, note that the source-destination pair for each request is determined randomly. Figure 2 shows that PLR outperforms the other algorithms. For low traffic loads, SPF is the first algorithm to produce blocking. Both PLR and NAW start blocking almost at the same time, for 500 requests. Then, the gap between them increases with heavier traffic loads. For very high traffic loads, the SPF curve becomes closer to the PLR curve. This is normal since SPF consumes a lower quantity of wavelengths, enabling it to find free resources with a heavier load. In practice however, high blocking probabilities, which are greater than 40%, are not acceptable. To explain more about resource balancing, consider Figure 3 which plots the mean lightpath’s length versus the number of connection requests. Note that PLR lengths are very close to shortest path lengths, which indicates that PLR uses fewer resources than NAW and LCP. Also, lightpaths become shorter as the traffic load increases, confirming the effect of the lightpath’s length on the blocking performance. Indeed, as resources become scarce, it becomes increasingly more difficult to respect the continuity constraints. Consequently, only short lightpaths are feasible.

V. CONCLUSION

This letter proposes an adaptive routing algorithm which is based on routing information from the optical layer. This algorithm is simple, and contrary to current algorithms, it does not require the exchange of large quantities of routing information. The critical effect of the lightpath’s length on the overall blocking performance was identified, and a simple penalty function to limit this length was proposed. Numerical results confirm the presented claim and show that PLR outperforms all other algorithms recently proposed in the literature. As for future work, these promising results suggest that further studies need to address penalty functions.

REFERENCES


